A new way to produce conformal cooling channels by RPT for moulding blocks of the hybrid moulds

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Abstract

Hybrid moulds are an increasingly considered alternative for prototype series or short production runs. In this solution of injection moulds the moulding elements (blocks or other inserts) are manufactured in alternative metallic materials or in synthetic materials. One of the main issues associated to the use of these alternative materials is their thermal behaviour. For instance, in order to allow uniformity in the cooling of the moulded part, and a significant cooling time reduction, conformal channels are recommended as an efficient solution. The layout of the channels should contour the geometry of the impression, and has to be easily implemented during the production of the moulding blocks.

This paper reports on a case study involving the use of conformal cooling channels obtained in wax by 3D-impression. An injection hybrid mould of a simple geometry production was used for testing several possibilities of conformal cooling construction. The discussion of cure parameters of the epoxy-based composite resin that can have influence on the wax thermal properties is presented alongside with recommendations for the use of this rapid tooling technique.

Introduction

In last years the plastics industry has been trying to fulfil the needs of the market by faster product development, lowering costs and reducing time to market. In this context the moulding industry also used new technologies and techniques in the manufacturing chain to reduce product development time and reducing tool costs [1]. New alternative methodologies for design and fabrication of production tools of prototypes and short runs of plastic were envisaged [2]. Within these the concept of hybrid mould has been developed to resolve new needs of the plastic industry [3].

Hybrid moulds are a design solution where conventionally machined structures are assembled with moulding blocks (core and/or cavity) produced by rapid prototyping and tooling (RPT). Typically these blocks are produced in soft materials (e.g. epoxy resins), allowing easier manufacturing and short delivery time [1]. Hybrid moulds are an increasingly considered alternative for prototype series or short productions runs [3-5]. Various RPT techniques are being used in the manufacturing of hybrid moulds [5]. However, there are problems associated to the use of the alternative materials often used with RPT. The epoxy resins have low thermal conductivity, compared with standard tool steel normally used in injection moulds. This problem implies a longer cooling time, causing an increase in the cycle time and changing properties of the product [6].

The use of materials with different thermal properties in the moulding blocks lead to the need of adjustment of the cycle program and the processing setup. In recent studies reported elsewhere [4] it was observed that the use of these materials affect the shrinkage of the moulded part and originate distortion with respect to the original shape. To solve these issues it is recommended to increase the thermal conductivity of the epoxy composite and make more uniform the temperature of the moulding surfaces. One possibility is the incorporation of conformal cooling channels within the mould.

A technique that can be used to make the conformal cooling channels is the fusible core. This technique allows the production of extremely complex parts with internal geometries that cannot be conventionally demoulded. It requires an inner core component to be cast in an alloy with melting point lower than the moulded polymer. This core works as an insert in the mould prior to the injection moulding of the polymer [7, 8]. After moulding and/or curing, the part is heated and the core is melted out at a temperature that must be kept low enough not to cause damage or distortion to the product [8]. In choosing the alloy for the core, it is important to reconcile the alloy melting point with the working temperature over moulding, curing and melt-out. The mechanical properties of the fusible core are also to be considered, especially to withstand the high pressures occurring during the injection moulding cycle. The ability of the core to keep its shape, to guarantee the required interior finish of the part, and the energy consumption are also to be considered [7-9]. Finally it is recognised that this technique has the advantages of producing more homogeneous parts, elimination of components, and better

cost/quality ratio resulting from the reduction of secondary assembly operations (e. g. welding) [9].
For the manufacturing of conformal cooling channels the *ThermoJet* three-dimensional printing system (3D Systems, EUA) is seen as a possibility [11]. As the *ThermoJet* is an additive rapid prototyping (RP) process, there is the need to use support material, which increase consumption of material and the need of a finishing operation [10].
The main objective of this study is to evaluate the use of conformal cooling manufactured in wax by 3D-impression, in injection hybrid moulds.

Experimental

Mouldings

The main dimensions and design details of the plastic part are illustrated in Figure 1. The moulding is 2 mm thick and features a rectangular opening of 40x65 mm.

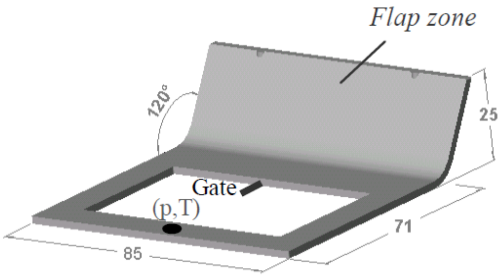

Figure 1 – Geometry of the plastic part

Mould

The moulding blocks of the injection hybrid mould to produce the plastic part are a interchangeable core and a steel plate as the cavity (Figure 2). The mould is instrumented with an integrated pressure and temperature sensor (Kistler type 6190BA) to collect the data at the end of filling where a weld line forms (point (p, T) in Figure 1). The sensor is located in the mould cavity side.

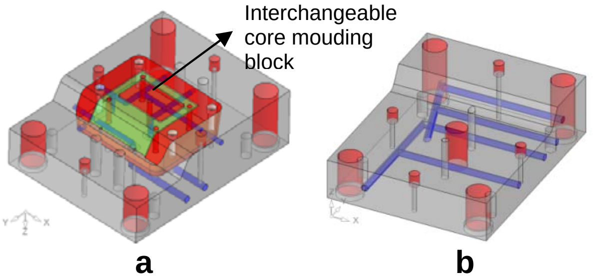

Figure 2 – The moulding blocks: a) core, b) cavity

Material

The moulding blocks were produced by vacuum casting in epoxy resin (Biresin L74) with 60% (in weight) aluminium powder.

The aluminium powder used in this composite has average particle size of 50 µm specific gravity of 2,43 $Mg.m^{-3}$. The thermal and mechanical properties of epoxy resin are shown in Table **1.**
Table **1**

Table 1 – Properties of the epoxy composite

Properties	***Units***	***Biresin L74 + 60% Alum.***
Specific gravity	$[Mg.m^{-3}]$	1.65
Specific heat	$[J.kg^{-1}K^{-1}]$	1279.19
Thermal conductivity	$[W.m^{-1}.K^{-1}]$	0.61
Thermal diffusivity	$[m^2.s^{-1}]$	$0.29x10^{-6}$
Thermal expansion coefficient	$[K^{-1}]$	$6.00x10^{-5}$
Flexural modulus (20ºC)	[GPa]	5.00-6.00

Conformal cooling channels

The layout of the cooling channels is illustrated in Figure 3. The use of RP to make the conformal channels allows designing the layout that best fit the shape of the part, namely making curved cooling channels impossible to obtain by conventional machining.

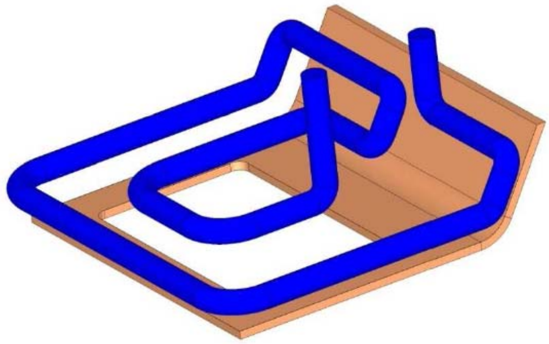

Figure 3 – Layout of the conformal cooling channels

The conformal cooling channels were produced by a *ThermoJet* solid object printer. The deposition of the wax-like thermoplastic is made by an extrusion head that deposits a thin layer with the geometry of the section for each layer of the model. Figure 4 shows the conformal channels produced with the *ThermoJet* printer. It is also shown the supports that the system automatically creates for the part.

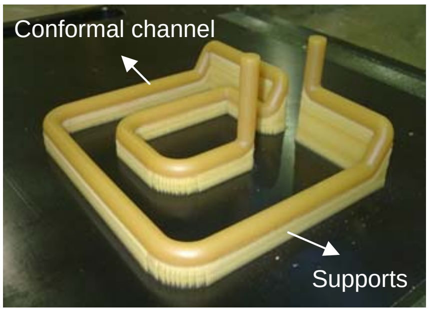

Figure 4 – Conformal channels obtained with the *ThermoJet* printer

The properties of the *ThermoJet* wax material are shown in Table 2.

Table 2 – Properties of the *ThermoJet* wax material *

Properties	***Units***	***TWax***
Specific gravity	[$Mg.m^{-3}$]	0.97
Viscosity @ 135 ºC	[Pa.s]	0.01
Melting point	[ºC]	80-90
Flexural yield stress	[MPa]	5.52
Flexural modulus (20ºC)	[GPa]	0.21

* Source: *Soliddo*, s.l. (Barcelona, Spain) data sheet

After removing the supports, the conformal channel is positioned into a support box, and the resin is cast (Figure 5).

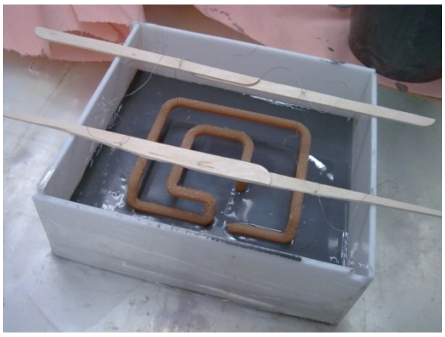

Figure 5 – Conformal channels positioned into the support box and epoxy composite being cast

Temperature monitoring

The cure of epoxies is an exothermic process which makes necessary to monitor the thermal evolution of the process. This was made using a USB TC-08 thermocouple data logger system (Picotech, UK). In order to achieve the correct reading three channels were used, each of them making a reading every 33 s.

The calibration curve of the Pico system is depicted in the Figure 6. It can be seen that the temperature of the thermocouples stabilizes at 99ºC, very close for 100ºC. Therefore the associated error is negligible.

The monitoring of the temperature during the cure of the epoxy shows that the maximum temperature is approximately of 170ºC (Figure 7).

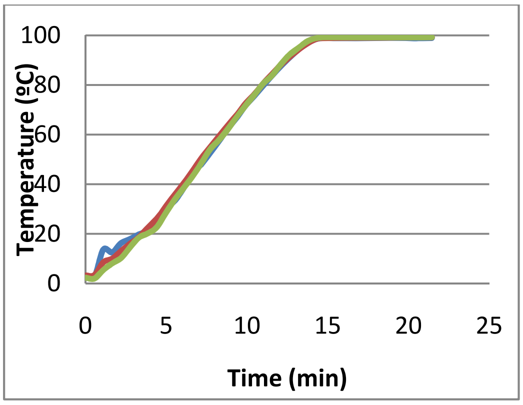

Figure 6 – Type K thermocouple calibration curve

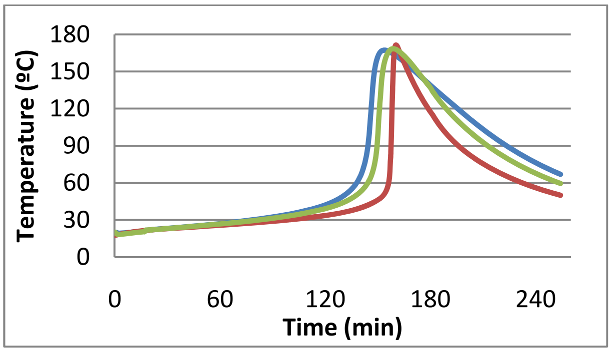

Figure 7 – Thermal evolution of the epoxy composite

Results and discussion

During the cure of the epoxy composite it was verified that the wax conformal channel was melted, as shown in Figure 8.

Figure 8 - Wax conformal channels melted during the epoxy resin based composite cure

The problem is related with the temperature rise during the exothermic cure and the melting temperature of the wax material.

An alternative solution was envisaged of making a preliminary coating of the conformal channel with a layer of epoxy composite (Figure 9). This epoxy layer is expected to confer geometric stability to the wax core during heating.

Figure 9 - Wax conformal channels coated with the epoxy composite

Nevertheless this alternative did not work out as the epoxy coat did not keep the wax material.

This partially unsuccessful study shows that a detailed heat transfer analysis is required before using this RP alternative to produce conformal cooling channels. This analysis will enable to balance the heat required by the wax to melt and the heat released during the exothermic cure of the epoxy resin.

The heat required by the wax material before its melting temperature can be calculated by the equation (1):

$$Q = m \times c_p \times \Delta T \qquad (1)$$

where Q is the amount of heat, m is the mass of the wax material used, c_p is the specific heat capacity and ΔT is the difference between the wax melting temperature and the room temperature.

The exothermic heat released during the cure of the epoxy is described through the energy conservation equation (2), which includes an exothermic heat generation term given by an appropriate kinetic model.

$$\frac{\partial}{\partial t}(\rho h) + \frac{\partial}{\partial x_i}(\rho u_i h) = \frac{\partial}{\partial x_i}\left(k\frac{\partial T}{\partial x_i}\right) + \rho H\frac{\partial \alpha}{\partial t} \qquad (2)$$

where h is the specific enthalpy of the resin, k is the thermal conductivity, H is the exothermic heat released during the curing reaction per unit of mass, α is the fractional conversion (amount of solid material formed), and $\partial\alpha/\partial t$ is the rate of gel formation described by the kinetic model [12].

Many phenomenological models have been developed for the curing simulation of thermosetting materials. These models, assuming that only one reaction can represent the whole cure process, are expressed by the equation [12]:

$$\frac{\partial \alpha}{\partial t} = K(T) \cdot f(\alpha) \qquad (3)$$

where $f(\alpha)$ is a function of conversion (α) and $K(T)$, the rate constant, a function of the temperature.

This study is still under investigation. In the near future new experiments will be carried out to validate the use of fusible materials to produce conformal cooling channels for moulding blocks of hybrid moulds.

Conclusions

Conformal channels made by rapid prototyping using a low temperature melting wax can be seemingly considering for making the cooling system of hybrid moulds more efficient. They are a solution that compensates the limitations resulting from the low thermal conductivity of the epoxy composites used in moulding blocks.

Nevertheless there remains the need of preventing the fusible core for the conformal channels melting before the cure of the epoxy composite. This will require that the heat release during the resin cure is predicted. From this datum the wax type and the channel minimum volume can be more appropriately chosen.

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